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Application of three-component VSP technology at seismically difficult sites: An example from the FutureGen 2.0 site, Morgan County, Illinois, USA

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Abstract

Reflection seismic data provide the primary technology for imaging subsurface geology between and distal to wellbores; and where rock physics properties are suitable, surface seismic and vertical seismic profiles (VSP's) can provide important CCUS monitoring modalities. In addition, seismic data provide the subsurface framework for locating microseismic events and reducing risk of induced seismicity.

Seismic surveys have traditionally been limited to acquisition and processing of compressional (P) -wave data, but modern technology includes the use of three-component receivers that can additionally record shear (S) wave modes that have been generated at the surface or converted from P-waves in the subsurface. Each collected waveform can potentially produce a separate data volume and new information on the subsurface. This paper reviews the insights gained through application of multicomponent VSP technology at the FutureGen2.0 site where, typical of many proposed CCUS and CCS sites, traditional P-wave surface seismic imaging is considerably impacted by seismic noise.

We conclude that a comparison of shear and P-wave data and interferometric processing allows a better understanding of subsurface geology, and provides input parameters for improved acquisition of surface seismic data at CCUS sites in old, fast rocks or below depleted oil and gas fields. Although results will vary by locality, we suggest that because of the insights provided by an analysis of multicomponent data, multicomponent acquisition and processing should become part of standard best practices for site characterization and evaluation.

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Keywords: Three component VSP, FutureGen2.0, Mt Simon, Illinois Basin

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1. Introduction

Two 2D P-wave surface seismic lines, totaling 24 km, were acquired in 2011 as part of the screening process for the FutureGen 2.0 site in the western Illinois Basin (Fig.1). These data confirmed that no large scale faults are present at the site, but details of the images below about 500 m are heavily degraded by P-wave signal attenuation and by unidentified sources of seismic noise. A 2011, 193 km regional seismic line shot by the Illinois State Geological Survey [1] about 3 km north of the FutureGen site also displayed considerable loss of P-wave signal and increase in seismic noise below about 600 m as the line approached the western part of the Illinois basin.

Where rock physics properties are suitable, surface seismic and vertical seismic profiles (VSP's) provide important monitoring modalities for operating carbon storage projects [2, 3]. In addition, surface seismic and VSP data provide the geologic framework for locating and interpreting events detected by microseismic monitoring, the cornerstone of real-time geophysical monitoring technology at many sites [4, 5].

Modern three-component surface seismic and VSP receivers can record shear (S) wave modes that are generated at the surface or converted from P-waves in the subsurface (e.g., P wave down to the reflector- vertically oriented Sv to the receiver). Each collected waveform can potentially produce a separate data volume and new information on the subsurface.

Seismic P-wave energy is affected by both fluid and rock properties; shear wave energy travels only through the rock matrix. An analysis of converted seismic waves allows for improved lithologic and stratigraphic discrimination as well as better estimation of rock and fluid properties. Multicomponent seismic technology is especially applicable to the evaluation of reservoir porosity, along with identification of fractures and evaluation of seal integrity. Comparisons of P and S wave data provide information on presence of fugitive gas phase; and shear wave splitting can provide azimuthal information on presence and density of fractures or faults. Hardage et al. [6] have proposed expanding the constraints of P-P mode seismic interpretation to examining the potential of all modes (including P-Sv, Sv-Sv, and Sv-P) of the seismic elastic wavefield. This paper reviews the results of three-component VSP data acquisition with P-P and P-Sv processing at the FutureGen2.0 site in Morgan County, Illinois, the lessons learned, and the potential of converted wave data for improving imaging of storage sites that have seismic challenges.

The FutureGen 2.0 site is on the flank of the northeast trending Sangamon Arch, in western central Illinois. Geologically, this part of the Illinois basin has been subjected to non-deposition and erosional events that separately truncate units in the Pennsylvanian, Mississippian, Devonian and Silurian strata, in addition to more regional erosional events associated with the Knox unconformity that occurs around 625m in the stratigraphic well #1 (FGA#1) (Fig.2). As a result, this site is expected to possess considerable site-specific vertical and lateral acoustic and lithologic heterogeneity.

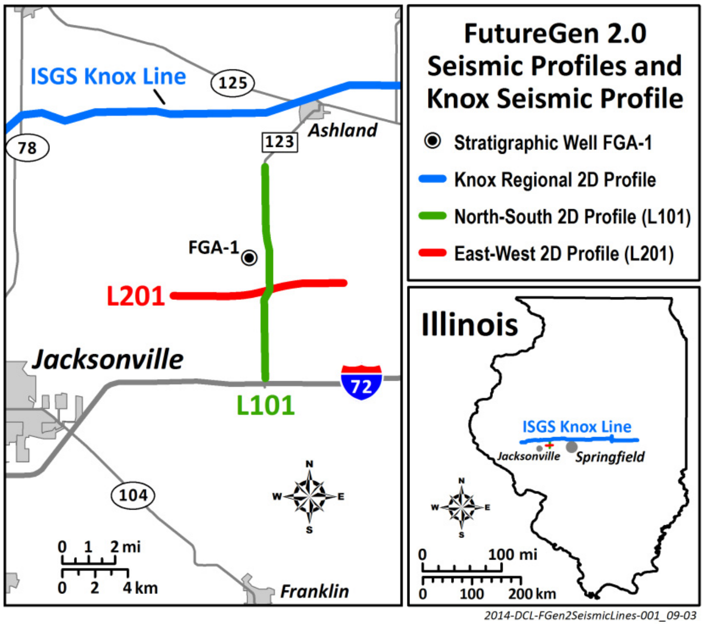

Fig. 1. Location of the FutureGen 2.0 Morgan County carbon storage site, 2D seismic lines, and VSP well.

2. Objectives and Methods

The 2011 2D surface seismic poorly imaged the tops and internal stratigraphy of the Eau Claire seal and the Elmhurst/Mount Simon storage target (Fig.3). The 2013 VSP survey was planned and acquired to focus on resolving the P-wave seismic data quality issues and to determine best practices for future acquisition of surface seismic, as well as to investigate the potential of VSP technology and converted wave modalities for improving the resolution and imaging of the intervals of interest.

The 2013 borehole seismic program at the FutureGen 2.0 CO_2 storage site consists of a zero-offset and 15 offset locations (Fig. 4). The VSP receiver well is the 1470 m FGA#1, a vertical stratigraphic well, drilled in late 2011. The Elmhurst/ Mount Simon sandstone storage target is between 1174 m and 1351 m, and the lower part of the well was uncased from 1229 m to 1470 m. The well is located in a rural area northeast of Jacksonville, Illinois. Site access for seismic source trucks is good, with fairly level topography; but off-road acquisition is limited to winter because of crop production.

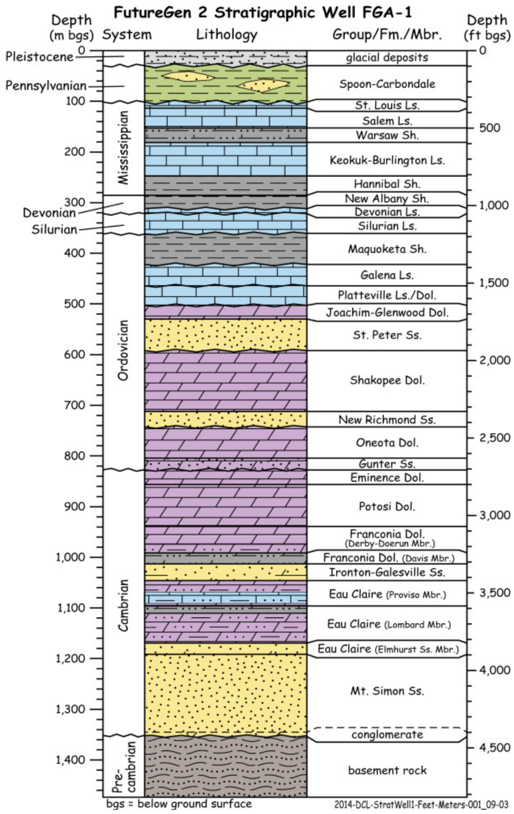

Fig.2. Stratigraphy encountered in the FutureGen 2.0 Stratigraphic Well #1. Vertical lithology changes and multiple unconformities may contribute to the generation of seismic noise.

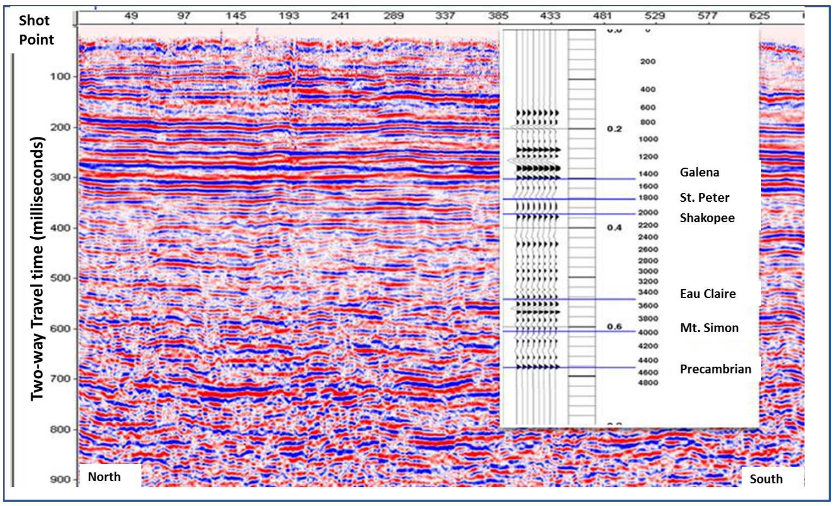

Fig. 3. North-south P-wave 2D surface seismic line from the Morgan County Site, with projected synthetic seismogram from the FGA#1. An example of surface statics is visible between shot points 145 and 193; attenuation and degradation of signal are obvious below 400 ms and details of the Eau Claire seal and Mount Simon storage formation are poorly imaged. Field of view is 13km. Scale on the synthetic seismogram is in feet; 1ft = 0.3048 m.

Data acquisition was conducted at the zero-offset position and 15 of the originally designed 17 source stations with a 20 level array of 3 component receivers at 15m vertical spacing. The total number of receiver stations ranged from 89 to 40, as noted in Fig.4. The seismic source was generated by one vibroseis truck, and the single-sweep frequency was 6-120 Hz with 16 seconds length. The VSP's at the 15 offset source stations encircled the receiver well as a sparse walk-around VSP. The walk-around geometry generated a spoke wheel of 2D images, centered on the stratigraphic well. Data from Stations 9, 8, 7, and 5 allowed processing as a short walk-away survey.

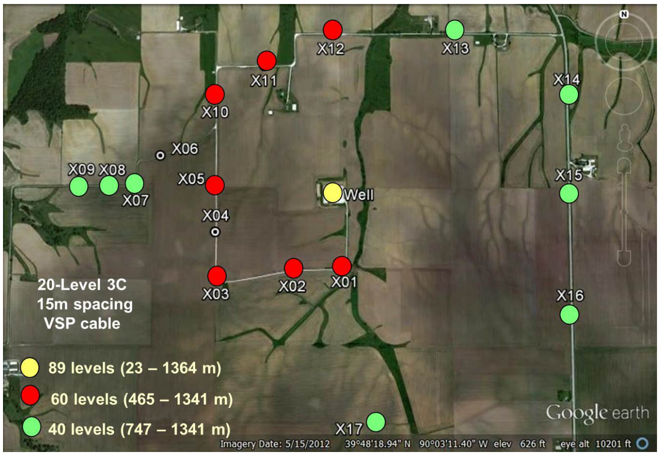

Fig.4. Zero offset and offset source points, and depths of geophones for the 2013 FutureGen VSP program. Distance from the well to Station 15 is 1219m.

Logs from the receiver well and geophone positions are shown in Fig.5. The highest receiver position was 23 m below the surface. Data acquisition in the shallow part of the borehole is important for the zero-offset location. VSP image width increases as the heights of receiver stations increase above the target. The outer edge of a VSP image is often deleted for offset stations for multiple reasons including distortion due to limited aperture of the sensor array, velocity errors, the increasing horizontal direction of approach angles of raypaths traveling from the farthest reflection points, and because of raypath refractions.

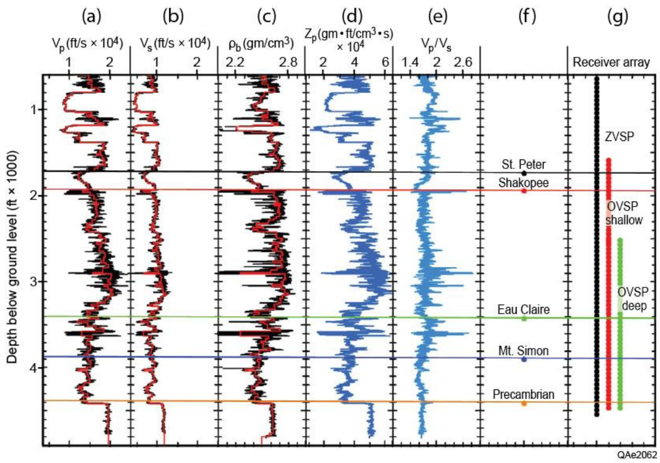

Fig.5. Logs and geophone positions in the FGA#1 VSP well. The number of receivers varied by offset source location. Log curves from left to right are (a) blocked P and (b) shear wave velocity, (c) blocked bulk density, (d) P-wave impedance, (e) Vp/Vs ratio, (f) formation tops and (g) geophone coverage.

3. Seismic Processing and Results

The processing of zero-offset VSP data acquired in a well that penetrates horizontal beds as at the FutureGen site is a simple procedure that requires only that (1) downgoing and upgoing wavefields be separated, and (2) a deconvolution operator be applied that attenuates multiple events in the upgoing wavefield. When these two steps are done, the upgoing wavefield can be converted into a front-corridor stack. The value of a front-corridor stack is that it: (a) is dominated by primary reflection events, (b) defines the depth origin of each primary reflection event, (c) serves as a key interpretation tool to determine if far-offset VSP images are reliable, and (d) defines primary reflection events in surface-recorded seismic data. The P-P front-corridor stack created at the FGA#1 well is shown in Fig. 6. For the offset VSPs, processing included three component orientation, vector wavefield decomposition, and 2D Kirchhoff migration to prepare the data for imaging and converted wavefield analysis.

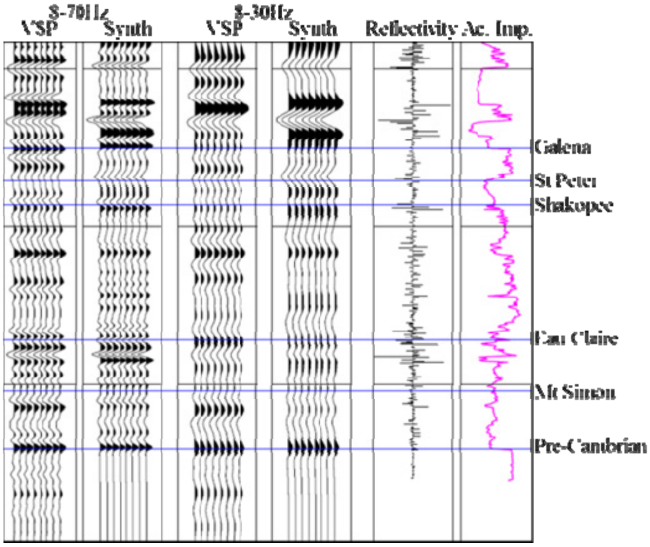

Fig. 6.Front-corridor stacks, P-wave synthetic seismograms, reflectivity and acoustic impedance. Interbedded shales and limestones dominate the interval above the Galena limestone; the craton-wide Knox unconformity occurs at the top of the Shakopee Formation (Knox Supergroup).

3.1. Identification of Sources of Seismic Noise

Examination of intermediate processing products helped determine depths and types of features that contribute to seismic noise and attenuation of signal at the Morgan County site. This section addresses multiples, attenuation, and mode conversion. Although surface statics were not specifically analyzed, the vertical data disruptions observed in the surface P-wave data are not present in the VSP data.

Primary reflection events are created at acoustic impedance boundaries by the downgoing first arrival, and upgoing multiples are created at these same interfaces by downgoing events that arrive at later times. VSPs are ideal tools for identifying seismic multiple reflections, particularly inter-bed or peg-leg multiples. Outside-corridor stacks should be free of inter-bed multiples after trace-by-trace wave-shaping deconvolution. Inside-corridors will contain inter-bed multiples. Fig. 7 shows three possible multiple generators in the P-wave inside-corridor stack. The multiple generators coincide with interfaces between shallow shales and limestones and deeper unconformities. By adaptively subtracting the inside-corridor stack from the outside-corridor stack, a VSP multiples model can be produced for removal of multiples during processing of surface seismic.

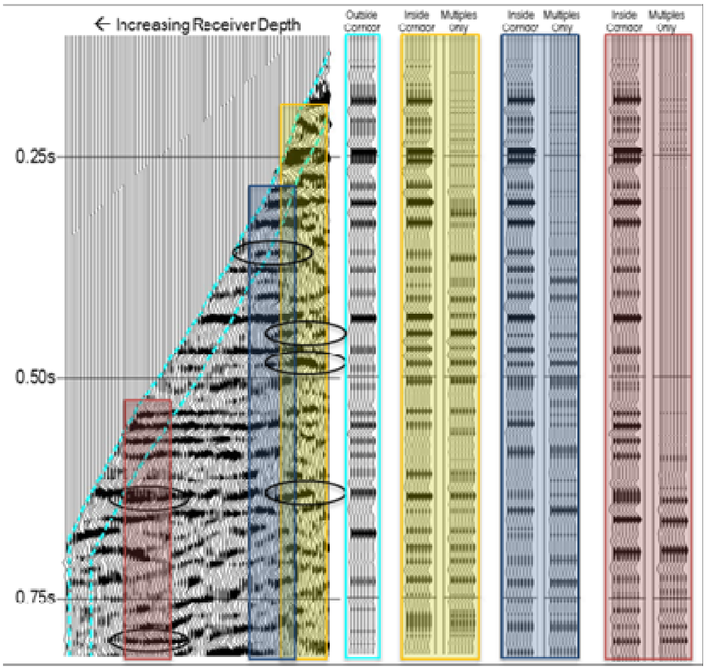

Fig. 7. Zero-offset VSP upgoing wavefield. False reflectors generated by multiples are circled in the inside- corridor stack (yellow).

Analysis of the losses caused by seismic attenuation in the zero-offset P-wave VSP indicates that there are two attenuating zones within the Pennsylvanian rocks of the first 122 m of the subsurface and near an unconformity at 427m at the top of the Galena limestone. Evaluation of the Sv wavefield extracted by the three-component vector wavefield decomposition from one of the OVSPs identifies additional attenuation zones near unconformities at the base of the New Richmond sandstone and at the base of the Ironton sandstone. Surface seismic is affected twice by these features. Attenuation in the shallow Pennsylvanian section is likely caused by methane associated with thin coals as well as noncommercial traces of natural gas. As expected, the P-Sv data are far less affected by attenuation.

3.2. Mode Conversion and Direct Shear Generated by Vertical P-wave source

Depth of mode conversion can be determined by analyzing the horizontal components of the zero-offset VSP and the Sv wavefield extracted by the three-component vector wavefield decomposition from the OVSPs. Fig.8 shows that within the zero-offset VSP, there are strong converted waves generated from events at approximately 152m, 366m, top of St. Peter, and at the Knox unconformity at the base of the St. Peter. OVSP analysis indicates mode conversion as well as attenuation occurs near the unconformity at the top of the Eau Claire seal.

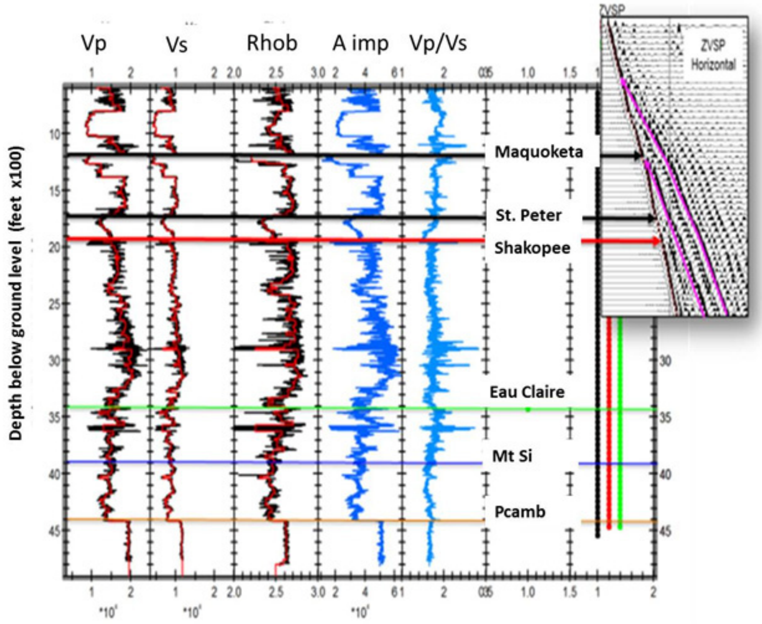

Fig.8. Depths of seismic mode conversion at the base of the St. Louis limestone, top of the Maquoketa shale, top of the St Peter, and at the Knox unconformity, as observed in the zero-offset VSP horizontal wavefield. Offset VSP data indicate additional mode conversion at the top of the Eau Claire seal. Vp and Vs are P and S wave velocities, Rhob is bulk density, Aimp is acoustic impedance.

Direct-S modes can be generated at the surface by standard vertical P-wave sources [6]. The advantage of direct-S modes is that S-S images can be constructed with standard common-midpoint (CMP) rather than by specialized common-conversion-point (CCP) software required for imaging P-SV data.

Zero-offset data, with receivers extending upward to within a few meters of the surface allow downgoing S modes to be tracked back to point of origin. The data shown in Fig. 9 are the response of what is labelled as a NRY geophone. The NRY is a hypothetical geophone that is mathematically rotated in two steps in VSP data space. The result is that NRY data emphasize downgoing (converted) Sv modes. Two downgoing events are marked on the data. The downgoing P first arrival should not be recorded by a NRY geophone since a NRY geophone is essentially perpendicular to a downgoing P raypath (and thus perpendicular to the P particle-displacement vector). The line labeled “direct-P” shows where the direct-P mode would be if it existed in the data. A key point illustrated by these data is that there is a “direct-Sv” mode that extends back to the vertical vibrator source station and has the same origin time as the direct-P mode. This demonstrates that the vertical vibrator deployed across the sequestration site is generating both direct-P and direct-S modes. Thus future S-S imaging of the geology across the site with a vertical vibrator is feasible.

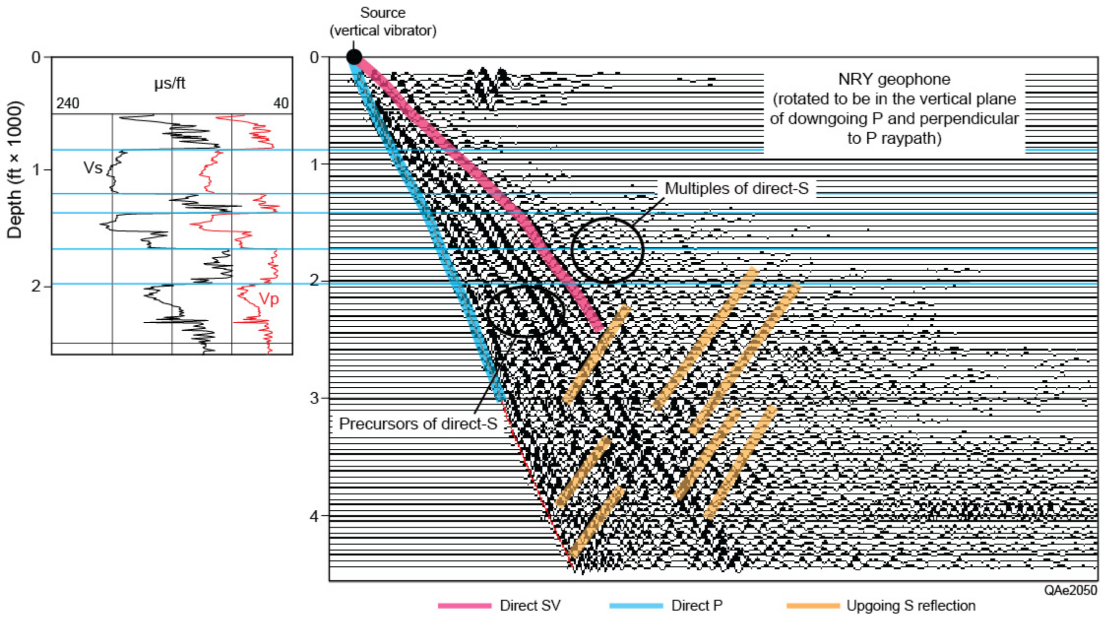

Fig. 9. NRY geophone response associated with the zero-offset VSP data demonstrates the presence of direct (down-going) shear wave mode, created at the surface by the vertical vibrator. Note seismic noise created by multiples of the direct S mode. Log depth with velocity for shear (Vs) and P-wave (Vp) is in feet.

Shear wave splitting analysis indicated moderate anisotropy, but the low number of offset stations and the large angles between the offset VSP's precluded robust analysis with this survey. An analysis of the surface-generated fast shear wave data indicated the azimuth of maximum horizontal stress to be N65E for the overburden, which is comparable to the azimuth independently determined from full waveform sonic log data and separately from induced tensile fracture data in wellbore image logs.

Velocity models were constructed (not shown) from the data and include a flat layer model generated from the zero-offset data, and 2.5 D velocity models, one for each offset station, with anisotropy that best fits data from each station. Velocity pull-ups in P-Sv images compared with P wave images for identical stations indicate that additional removal of anomalous frequencies and modelling of the velocity field is still required to reproduce the correct velocity field for the site. These VSP velocity models will be updated with new VSP data and passive seismic data acquired in perforation of each of four horizontal injection wells in order to build the working 3D velocity model for microseismic monitoring of injection operations at the Morgan County site.

3.3. Seismic Images

The offset VSP's at the Morgan County site produced 2D seismic images that extend from 300 to 600 m away from the receiver well. The processed VSP data indicate no resolvable faults and no vertical seismic anomalies. As expected, both P-P and P-Sv data produced images of the Eau Claire seal and Mount Simon reservoir that have a higher frequency content and higher resolution than is present in the surface 2D P wave data. In addition to imaging six reflectors within the Elmhurst- Mount Simon interval, a velocity contrast at the base of the proposed injection zone is well imaged and easily mapped in both P-P (Fig. 10) and P-Sv data sets. Importantly, the P-SV VSP images have greater reflection strength, display less attenuation, and are higher resolution compared with the P-P images (Fig.11).

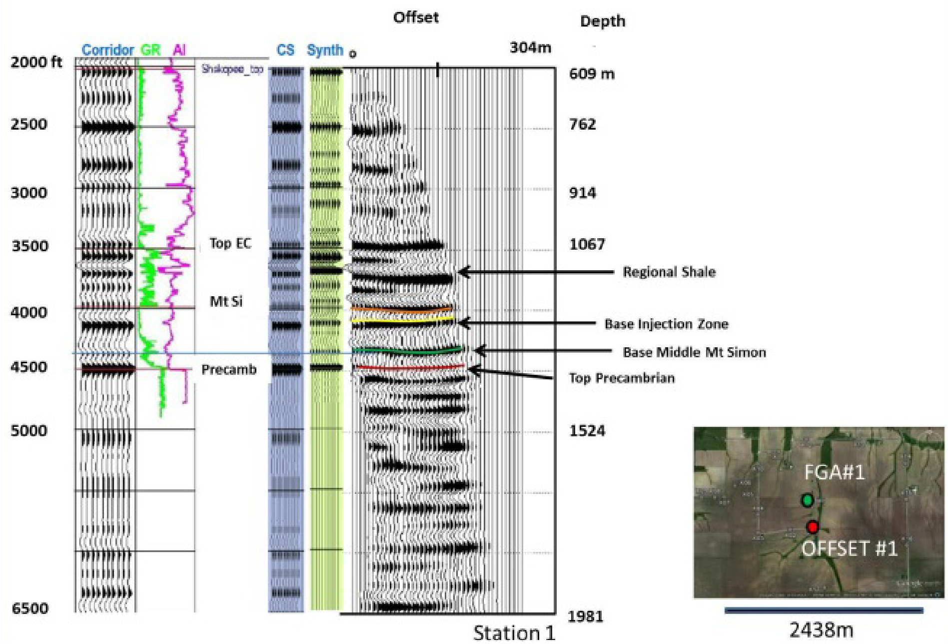

Fig.10. VSP P-wave details of the Mt Simon geology, along with the corridor stack, gamma ray, acoustic impedance, and P-wave synthetic.

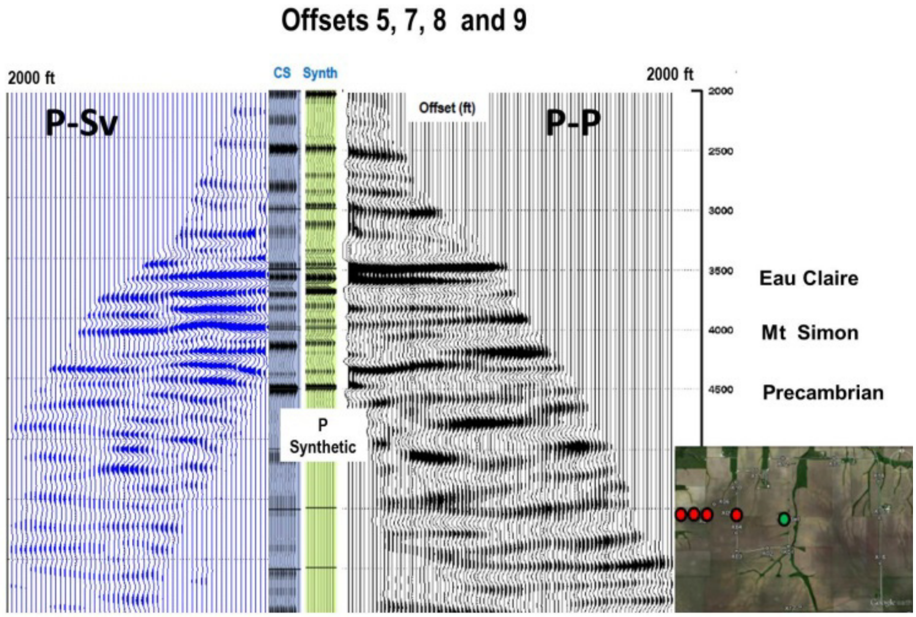

Fig. 11. Comparison of P-P and P-Sv images for combined offset stations 5,7,8,9, along with the corridor stack and the P-wave synthetic. Note the greater number of reflectors in the Eau Claire interval. Slight pull-ups in the P-Sv image compared to the P-P image indicate that high frequency shear multiples may still be present and that the P-Sv velocity model can be improved.

Images produced by interferometric migration of the VSP direct wave are less sensitive to velocity estimation and static errors [7]. An example of interferometric processing of the P-wave and P-Sv data is shown in Fig. 12. Again the P-Sv image has an increased number of reflectors for a given interval within the sedimentary section.

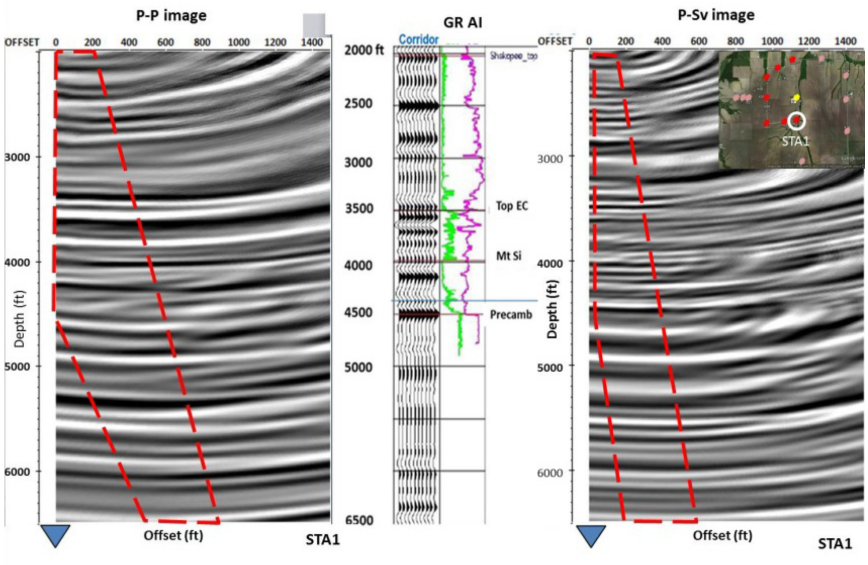

Fig 12. Comparison of P-P and P-Sv wave interferometric direct wave migration for Offset Station.1. Note increased number of reflectors above and in the Eau Claire interval of the P-Sv data. Red dashed outline shows area for interpretation.

4. Discussion

CCUS sites and many CCS sites will be in areas that have low saturations of natural gas above the CO_2 storage reservoir. Surface seismic P-wave energy at these sites will be attenuated. Thus, converted wave data will be essential for imaging potential above-storage-zone monitoring zones.

Although all of the images produced by the 2013 VSP program produced images that are far superior to the 2011 2D surface seismic images, 3D3C VSP and 3D3C surface seismic will provide better spatial placement of events than is provided by any of the 2D seismic methods.

Rock physics modelling indicates that the rock and fluid properties of the Mt. Simon and Elmhurst in the FGA#1 limit the use of seismic monitoring in detecting time-lapse differences in saturation of CO_2 within the reservoir. However, the comparison of VSP and surface seismic time-lapse P and S wave data is a demonstrated technology for detecting gas phase [8] and is a viable technology for detecting fugitive gas in the shallow overburden.

Intermediate processing products strongly indicate that the vertical vibrator source at the Morgan County site generated both direct-P and direct-S modes. Although processing of S-S mode data remains challenging, VSP S-S imaging of the geology across the area with a vertical vibrator appears feasible.

5. Conclusions

Acquiring three-component seismic data is becoming more common for improving imaging of CCS and CCUS sites. But even when acquired, converted-wave data are often underused or relatively unexamined. At the FutureGen2 site, an examination of processing products allowed identification of sources of seismic noise related to multiples and attenuation. Although offset stations were too sparse to determine shear wave splitting, fast shear wave data indicated the azimuth of maximum horizontal stress to be N65E for the overburden, comparable to the azimuth independently determined from sonic and image logs.

Morgan County P-wave VSP seismic images are highly superior to surface seismic P-wave images, and P-Sv data display higher resolution than P-wave VSP. Interferometric migration, being less subject to velocity anisotropy, particularly improves P-Sv imaging, and appears to be a technology with considerable potential.

Parameters derived from 3C datasets are vital to improve traditional surface seismic processing and to constrain velocity models for microseismic monitoring. Multicomponent acquisition provides insights for understanding or improving subsurface imaging in onshore areas with old, fast rocks, or under shallow oil and gas fields, typical of many areas being considered for carbon dioxide storage. Although efficacy will vary by site, we recommend that converted-wave seismic data become a standard part of subsurface characterization of carbon dioxide storage sites.

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